Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **High Temperature Superconductors for Naval Power Applications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**3**	

High Temperature Superconductors for Naval Power Applications

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Background and Significance: As the Navy moves to the all-electric warship, superconducting materials will play a key enabling role. High temperature superconducting (HTS) motors and generators will enable extended range, high-efficiency, high-power-density naval propulsion, and compact generators for weapons and ship systems. Compact mobile HTS generators also may provide portable/mobile power for littoral and expeditionary operation, naval air, and homeland security.

The "second generation" high-temperature superconductors (2G-HTS) based on yttrium-barium-copper-oxide (YBCO) "coated conductor" architectures are undergoing a processing technology breakthrough that will lead to large-scale manufacture by 2008. NRL is working with manufacturers to address key issues in the processing and performance of these conductors during this fast-paced stage of technology development.

In particular, 2G-HTS process development is accelerated by fundamental understanding of the materials microstructures gained at NRL. Key goals include reduction of AC losses in the HTS motors and generators, as well as novel inductor designs for power electronics. Ensuring superior fatigue properties of the HTS materials compatible with the lifecycle of naval machinery is a key objective.

Functional Performance: Figure 1 shows a schematic representation of the structure of a typical 2G-HTS tape. The superconductor is the thin (1 micron) layer of YBCO which is deposited by coating or thin-film techniques. The substrate for this superconducting layer is a series of ceramic buffer layers deposited onto a crystallographically textured nickel-alloy foil. For structural stability, laminations of copper-alloy foils are applied.

The superconducting properties depend upon the composition and processing of the YBCO layer. In particular, substitutions of rare-earth elements such as holmium for yttrium results in improvements in how the superconducting critical current Ic depends on magnetic field. In motor and generator coils, the magnetic field varies in direction, and thus the minimum value of Ic at any angle can be more limiting than the highest Ic value. NRL performs sophisticated high-resolution electron microscopy studies of 2G-HTS materials to determine what types of microstructural features form and how they are associated with desirable features of Ic vs field angle behavior. Figure 2 depicts some recent results, showing an Ic curve for a pure YBCO layer, with the sharp peak in Ic for magnetic field parallel to the layer, versus a holmium-doped YBCO layer, with a lower, but more uniform Ic. The most important types of microstructures detected by NRL are shown.

Fatigue Tolerance: High-power naval rotating machinery imposes more severe mechanical conditions than corresponding civilian applications. This is because reduced weight and volume are key drivers for this technology in the Navy, thus structural design of HTS coils is every bit as important as their functional capabilities. In particular, to ensure prospective service life of 30 years or more, potential for fatigue damage must be considered. One premier task area of the NRL program is evaluation of electromechanical properties of HTS tapes and coils, with special emphasis on fatigue tolerance. Figure 3 shows an example of an evaluation performed by NRL on a typical conductor. Figure 3(a) shows how the superconducting critical current Ic decreases with increasing peak applied stress. There is a critical stress below which the Ic changes are at least 95% reversible. Figure 3(b) shows the same conductor subjected to cyclic (fatigue) loading, indicating that cumulative degradation occurs with repeated loading. However, the change of Ic with cyclic loading eventually stabilizes, so that the conductors do not degrade indefinitely.

Cryogenic Inductors: Another element of the NRL program is development and demonstration of HTS inductors for cryogenic power electronics. Conceptually, if the generator and motor are both superconducting, then significant system efficiency benefits could be achieved if the power electronics converters and transmission lines between the generator and motor also operate in the cryogenic environment. Additionally, in conventional ship-drive-power electronics, inductors account for as much as 40% of the volume, 50% of the weight, and are the main source of power losses. Air-core superconducting inductors, however, by virtue of higher current density, can be made smaller and lighter than conventional iron-cored copper inductors. NRL is studying the loss mechanisms of HTS tapes and coils, as well as exploring novel inductor designs for minimizing losses.

Impact: Results of NRL's current program have influenced HTS manufacture for optimizing superconducting properties as well as validated conductor structural architectures for fatigue risk mitigation. Prototype coils are being evaluated for structural integrity

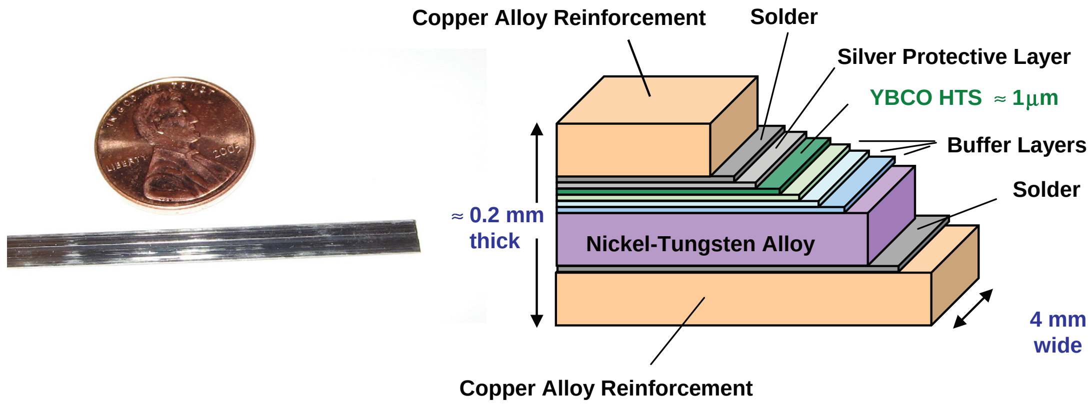


FIGURE 1
A typical 2G-HTS tape about 4 mm wide and 0.2 mm thick is capable of carrying as much as 80 A DC current at 77 Kelvin. Typical architecture of 2G-HTS tapes is shown schematically. The superconducting functionality is provided by the 1 µm-thick YBCO layer. The other 99% of the composite tape determines the mechanical properties.

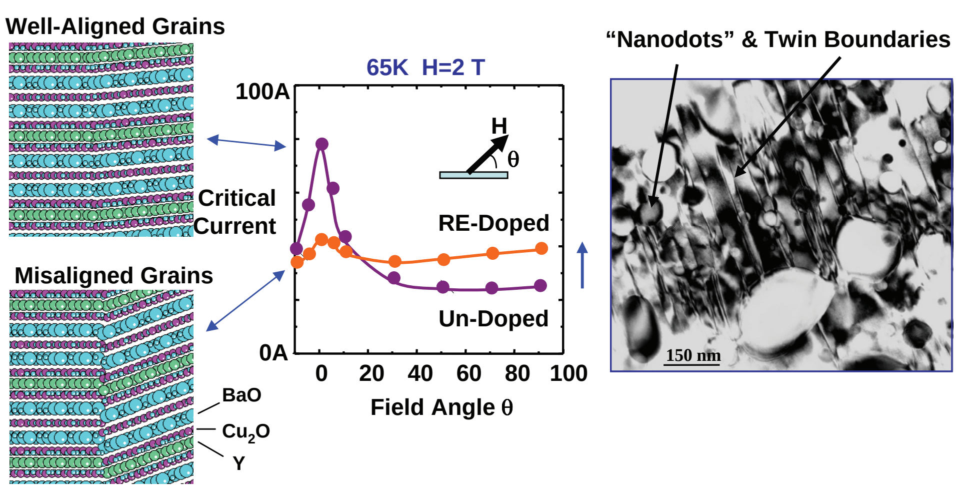
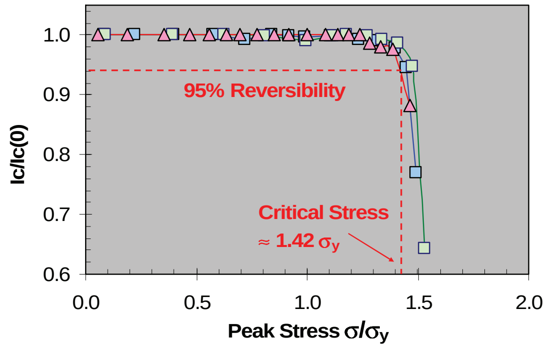
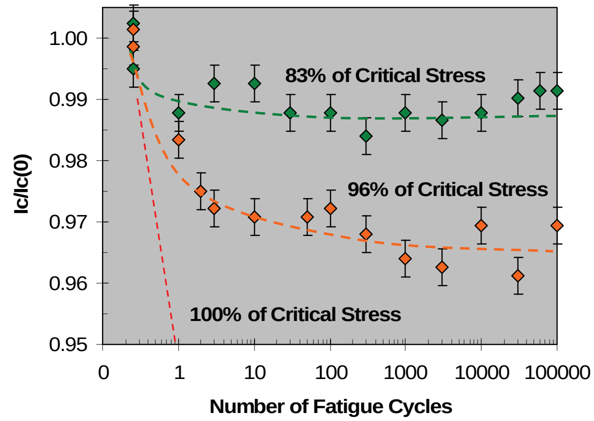


FIGURE 2
Relationship of microstructural defects to superconducting critical current behavior of 2G-HTS tapes in magnetic field, H. Maximum Ic for magnetic fields parallel to the tape is determined primarily by crystallographic alignment of the grains, while defects such as "nanodots" and twins improve the Ic for fields perpendicular to the tape. In this particular case, rare-earth doping decreased Ic for parallel fields due to reduced crystallographic alignment, but the nanoparticles and twin boundaries improve the perpendicular field performance.



(a)



(b)

FIGURE 3
Typical electromechanical properties of 2G-HTS tapes. Critical current drops as a function of maximum applied stress as shown in (a) for several tapes, but this effect is at least 95% reversible for stresses below some critical stress limit. Cyclic loading, (b), can cause additional fatigue degradation of Ic for stresses below the critical stress, but the properties stabilize after enough loading cycles. In these plots, Ic is normalized to its initial stress-free value Ic(0) and stress is normalized to the yield stress σ_y.

and AC loss performance. As the technology matures, NRL's contributions will include demonstration of practical inductors, composite coil design, and ultimately participation in large scale motor and generator demonstrations.

Acknowledgments: Superconducting tape and coil specimens used in this work are provided by American Superconductor Corporation, IGC Superpower, Inc., and Sumitomo Electric Industries.

[Sponsored by NRL and ONR]

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